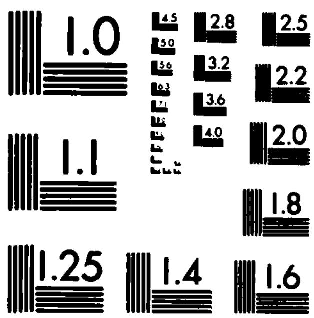
AD-A136 352 DESIGN OPTIMIZATION OF MARINE REDUCTION GEARS(U) NAVAL POSTGRADUATE SCHOOL MONTEREY CA W T BRAMLETT SEP 83 1/2

UNCLASSIFIED F/G 13/9 NL



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(2)

NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

DESIGN OPTIMIZATION OF MARINE REDUCTION GEARS

by

William T. Bramlett II

September 1983

Thesis Advisor: G. N. Vanderplaats

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
2. GOVT ACCESSION NO. AD-A136 352
3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle)
Design Optimization of Marine Reduction Gears
5. TYPE OF REPORT & PERIOD COVERED
Master's Thesis; September 1983
6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s)
William T. Bramlett II
8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS
Naval Postgraduate School
Monterey, California 93943
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS
Naval Postgraduate School
Monterey, California 93943
12. REPORT DATE
September 1983
13. NUMBER OF PAGES
105
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
15. SECURITY CLASS. (of this report)
Unclassified
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)
18. SUPPLEMENTARY NOTES
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Computer Aided Design; Design Optimization; Automated Design Synthesis; Marine Gear Design; Marine Gears; Helical Gears; Computer Aided Marine Gear Design; ADS; MARGO

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The development and use of the FORTRAN program MARGO (Marine Reduction Gear Optimization) is described. MARGO performs design analysis, weight minimization, and a rudimentary form of noise minimization using the general purpose optimization program called ADS-1 (Automated Design Synthesis, Version 1). Numerous subroutines are presented which calculate the associated design variables for marine

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Design Optimization of Marine Reduction Gears

by

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL

September 1983

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The development and use of the FORTRAN program MARGO (Marine Reduction Gear Optimization) is described. MARGO performs design analysis, weight minimization, and a rudimentary form of noise minimization using the general purpose optimization program called ADS-1 (Automated Design Synthesis, Version 1). Numerous subroutines are presented which calculate the associated design variables for marine reduction gears. The entire program is self-documented and easily modified by the user. Examples are presented to demonstrate the utility of the program.

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ACKNOWLEDGEMENT

I am indebted to Professor Vanderplaats for his willingness to be my advisor for this thesis. It was my utmost desire to write a thesis which would be of some practical use to the Navy. That Professor Vanderplaats was willing to advise me in the design optimization of marine reduction gears is a testament to his skill and confidence as an engineer. Professor Vanderplaats is a practical engineer who spends his research time writing programs for the benefit of design engineers. His optimization program COPES/CONMIN is widely used by NASA and numerous industries. His latest optimization program ADS-1 (Automated Design Synthesis, Version 1) is the foundation upon which my thesis is built. I greatly appreciate his patience, moral support, and most of all the inspiration and professionalism he has provided me throughout this endeavor.

I. INTRODUCTION

A. BACKGROUND

The gear design process is an iterative one. Like the "design spiral" approach used in naval architecture, the gear designer must iterate about an initial design point, assuming one value to find another. With each step, design variables must be compared to standards to ensure that vital constraints are not violated. The process is an arduous one and constantly subject to human error. New technologies, especially in the heat treatment of steels, change the initial design points and establish a new set of manufacturing limitations.

Perhaps the newest technology in machine design is CAD/CAM or "Computer Aided Design" and "Computer Aided Manufacturing." Much has been written about the revolutions sure to follow on the heels of high speed computers. While it is true that computers remove the engineer from the drudgery of computation and especially from the errors of computation, the "art" of engineering is still required. It is unlikely that a computer program will be written soon which can design a large machine without a great deal of human interaction. Therefore, the reader is cautioned that the program described in this thesis is not intended to replace the gear designer. Some engineers are apt to

look askance at any topic of engineering described with the word "computer." However, undergraduate and graduate engineers are taught that the advance of technology is aided by the use of computers. While experienced engineers have learned from many years of practice, the new engineer lacks experience but has a great deal of enthusiasm for applying computers to the solution of engineering problems.

The two key components for using a computer to solve engineering problems of design are logic and organization. The experienced engineer uses a logical approach to solve a problem. By formalizing the logical steps to solve a problem, the computer can be a useful tool.

One of the computer tools available to engineers is optimization. Mathematical in origin, research in optimization has resulted in several computer codes that have proven themselves reliable. Already widely used in the aerospace industry, it is time for marine engineers to apply optimization techniques.

B. THESIS OBJECTIVES

The three most important objectives of this thesis are to:

1. Apply the academic principles learned to an actual machinery design problem.
2. Introduce optimization techniques to the Navy's marine machinery design team.

3. Provide the Navy's marine machinery design personnel with an initial program which illustrates the application of optimization techniques.

To achieve these objectives, the design optimization of marine reduction gears was chosen as a topic. The primary outcome of the thesis is a program entitled "MARGO" for Marine Reduction Gear Optimization. MARGO is a master FORTRAN program which manages several groups of subroutines to calculate various design parameters for double reduction locked train gears like those illustrated in Figure 1, used in the Spruance class destroyer . MARGO also controls the access to the new general purpose optimization program titled "ADS-1" (Automated Design Synthesis--Version 1).

ADS-1 was written by Professor Vanderplaats of the Naval Postgraduate School in Monterey, California. Professor Vanderplaats is also author of the programs COPES (Control Program for Engineering Synthesis) and CONMIN (Constrained Minimization) which are widely used by NASA and industry. ADS-1 is a new general purpose optimizer and is described in Chapter II.

Because MARGO is written by a graduate student, there may be errors in judgement. Once again, the reader is cautioned that sound engineering judgement must still be applied to the factors which influence the outcome of a design. The adage "garbage in, garbage out" is an appropriate reminder and MARGO users are urged to review carefully

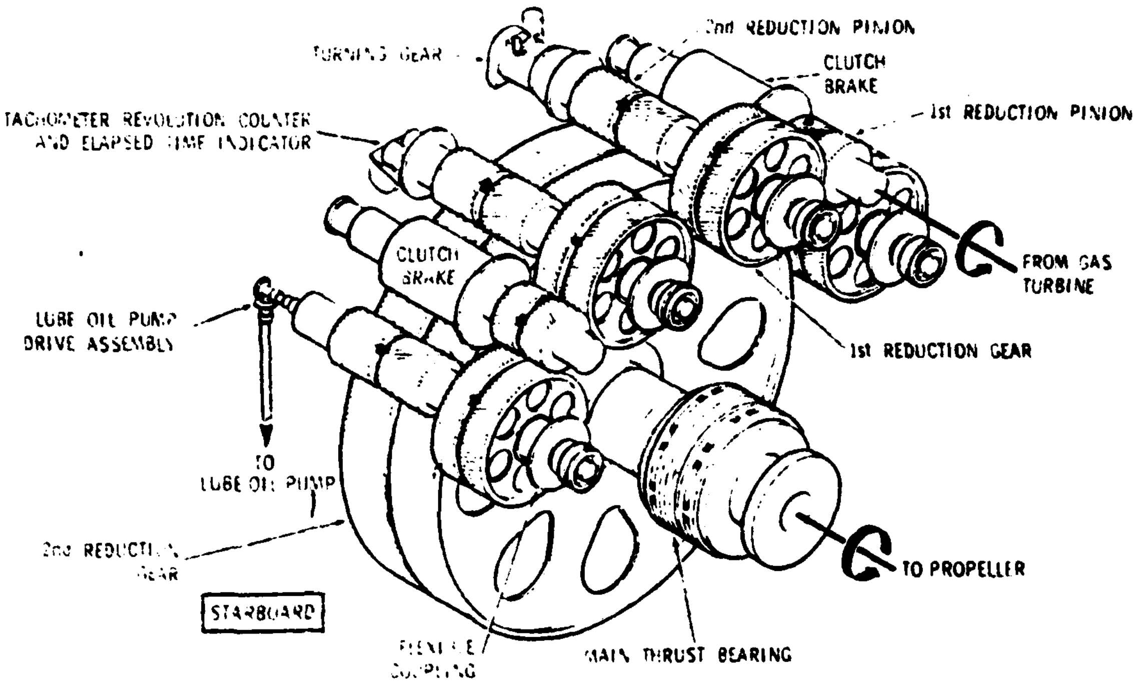


Figure 1. Double Reduction Locked Train Gears

the parameters used and those omitted. Nevertheless, MARGO should serve as an introduction to applying optimization techniques to marine machinery design.

II. OPTIMIZATION TECHNIQUES

A. PURPOSE

The purpose of this chapter is to introduce the general concepts of optimization and describe the optimization program used in this work. Further explanations of the concepts and methods discussed in this chapter are found in the references mentioned herein and in texts on the subject of numerical optimization.

B. GENERAL CONCEPTS

The general nonlinear constrained optimization problem is expressed in standard form as follows:

$$\text{Minimize} \qquad F(\underline{X}) \tag{1}$$

Subject to:

$$g_j(\underline{X}) \leq 0 \qquad j = 1,m \tag{2}$$

$$h_k(\underline{X}) = 0 \qquad k = 1,\ell \tag{3}$$

$$X_i^{\ell} < X_i < X_i^{u} \qquad i = 1,n \tag{4}$$

$F(\underline{X})$ is called the objective function and represents that property (e.g., weight or noise) which is to be

optimized. Since most optimizers are written to minimize the objective function, the negative of $F(\underline{X})$ is used when it is desired to maximize a property. For instance, if $f(X) = 5X + 10$ is to be maximized, then for the purposes of optimization the function is expressed as:

$$F(\underline{X}) = - f(X) = - 5X - 10$$

$F(\underline{X})$ may be a linear or nonlinear function of the design variables represented by the vector $\underline{X}$. Further, the objective function may be implicit or explicit in $\underline{X}$ but it should be continuous and have continuous first derivatives.

Equation (2) represents the inequality constraints which are imposed on the design. For example, if the stress is not to exceed 100,000 psi, then the constraint would be formulated as follows:

$$G = \frac{\text{Stress}}{100{,}000} - 1 \leq 0$$

A value of stress less than 100,000 psi will satisfy the constraint but a value in excess of 100,000 psi will result in a positive G and represents a violated constraint.

Equation (3) represents the equality constraints. For instance, a specific length over diameter (ℓ/d) ratio may be desired. If so, the expression $\ell = 1.5d$ would represent an equality constraint.

Equation (4) represents side constraints. Side constraints are the bounds, upper and lower, within which each design variable must remain. For instance, a pinion facewidth shorter than 10 inches or longer than 30 inches may be undesirable. When a constraint is equal to one of its limits (say pinion facewidth = 30 inches), that constraint is said to be active.

C. UNCONSTRAINED MINIMIZATION

There are two requirements for a solution to an unconstrained minimization problem:

i. The gradient of the objective function (i.e., the first derivative with respect to the design variables) must equal zero, and

ii. The Hessian matrix must be positive definite.

This last requirement means that the matrix of second partial derivatives of the objective function with respect to the design variables (the Hessian matrix) must have all positive eigenvalues. A positive definite Hessian matrix means that a relative minimum exists but does not guarantee a global minimum unless the Hessian matrix is positive definite for all possible values of $\underline{X}$. Unconstrained methods may be classified by the order of the derivatives required.

1. Non-Gradient Methods

Random Search is the simplest of all optimization techniques. The search for a minimum is literally a random

search within the defined design space. The combination of randomly selected $\underline{X}$ vectors which produces the minimum objective function is selected. The term "$\underline{X}$ vector" is used to describe a vector in which "n" is the number of design variables used in the problem. In order to ensure that an optimum has been located, the Random Search Method requires a very large number of evaluations. For this reason, Random Search is the least efficient optimization method. However, it is useful in those circumstances where computer memory is small and lends itself to use on hand-held calculators. Because of the large amount of machine time required to perform a random search, many variations have been devised to establish a "search direction" to improve efficiency.

Powell's method is probably the most efficient zero order method and was developed in 1964 [Ref. 1]. Based on the concept of conjugate directions, Powell's method conducts an initial search in n-orthogonal directions and updates the design by the following equation:

$$\underline{X}^q = \underline{X}^{q-1} + \alpha^* \underline{S}^q \tag{4}$$

where:

q = the iteration number;

α^* = the scalar step;

$\underline{S}$ = the vector search direction.

The new search direction is determined by connecting the last design point to the original design point; thus becoming the n+1, or conjugate, search direction. The method breaks down when no improvement is made to the objective function because subsequent search directions will not be conjugate. Also, after a few iterations the search directions begin to be parallel to each other due to numerical imprecision. Powell overcame these problems with a sophisticated technique but the simplest solution is to restart the process with unidirectional searches.

While there are other zero-order methods described in literature on optimization, the two methods described above give a suitable description of zero-order methods. The next level of improvement is to add gradient information and use first-order methods.

2. Gradient Methods

The simplest gradient, or first-order method is the Fletcher-Reeves Method of Conjugate Directions [Ref. 2]. The Fletcher-Reeves method is a modified form of the steepest descent method with an improved rate of convergence to a minimum solution. The search direction is selected according to the equation:

$$\underline{S}^q = -\nabla F(\underline{X}^q) + B^q \underline{S}^{q-1} \tag{5}$$

where:

$$\underline{B}^q = \frac{|\nabla f(X^q)|^2}{|\nabla F(\underline{X}^{q-1})|^2} \qquad (6)$$

∇ = "del" the gradient operator

$-\underline{\nabla}F(\underline{X}^q)$ = the direction of steepest descent

= $\underline{S}^{q-1}$ the previous search direction.

While the Fletcher-Reeves method offers improved efficiency, the Davidon-Fletcher-Powell and the Broydon-Fletcher-Goldfarb-Shanno variable metric methods for unconstrained minimization are more sophisticated and slightly more efficient. However, many engineering applications of optimization will involve constraints and require a different algorithm.

D. CONSTRAINED OPTIMIZATION

Constrained optimization techniques may be divided into two types, direct and indirect methods. Direct methods treat the constraints as limiting surfaces of the design space and search for an optimum within the feasible design space. Indirect methods transform the constrained problem into a set of unconstrained problems.

1. Direct Methods

Direct methods are popular constrained optimization algorithms. One well known direct method is the method of feasible directions [Ref. 3]. The method of feasible

directions determines a feasible search direction and then conducts a one-dimensional search in that direction. This one-dimensional search continues as much as possible without violating a constraint. Constraints which are active are used to establish push-off factors to redirect the search into the feasible region.

A recently developed direct method is the Robust Feasible Directions Algorithm developed by Vanderplaats in 1983. This algorithm combines features of the Method of Feasible Directions and the Generalized Reduced Gradient Method. A detailed description of this algorithm is presented in Reference 4.

2. Indirect Methods

A typical indirect method of constrained optimization is the Augmented Lagrange Multiplier method which uses penalty functions to contain or redirect the search into the feasible design space. Even if the initial design is infeasible, this method will still work. The Augmented Lagrange Multiplier method is explained in more detail in Reference 5.

E. ADS-1 (AUTOMATED DESIGN SYNTHESIS--VERSION 1)

ADS-1 is a powerful purpose optimization FORTRAN program for the solution of nonlinear constrained problems. Funded by a research grant from the National Aeronautics and Space Administration (NASA), ADS-1 combines many of the best

optimization algorithms into one program with a menu of optimization techniques from which to choose. Considerable effort has been spent developing and testing the algorithms presented in ADS-1. Reference 6 is a very thorough documentation of the speed and accuracy of the majority of the algorithms contained in a preliminary version of ADS-1 and research continues on the development and improvement of the program.

Since one of the primary objectives of this thesis is to introduce machinery design applications of optimization techniques and because ADS-1 is the optimization program used by MARGO, the following detailed information is presented from Reference 7 with permission of the authors.

1. Program Organization

One particular attribute of the ADS-1 program is its user friendliness. Armed with a fundamental knowledge of optimization, the novice can begin to use optimization immediately. As experience is gained and trust in the program develops, more and more uses of optimization will become apparent. While more experienced users will be able to select and modify the more sophisticated routines, it is not necessary to do so. To achieve this flexiblity, the program divides the optimization task into three basic levels:

i. Strategy--For example, Augmented Lagrange Multiplier Method;

ii. Optimizer--For example, the Method of Feasible Directions;

iii. One-Dimensional Search--For example, the Golden Section Method.

The ADS-1 program is actually a subroutine which calls subordinate subroutines to perform the optimization task as selected by the user. The user simply passes the desired options along with other information in the prescribed form of the ADS subroutine's calling arguments. The program's logic is illustrated in Figure 2.

When the user has set up the initial parameters (described below) and dimensioned the required arrays, the information parameter, INFO is set equal to -2. The ADS subroutine is then called. The user is then allowed to modify any control parameters, and ADS is called again for optimization. The ADS program initiates a search for the optimum by incrementally adjusting the design variables. After an initial adjustment is made, control is returned to the master program in order to conduct an evaluation of the objective and constraint functions which are defined by the user. The program recalls ADS and continues this process until no further progress is made in optimization. At this point the ADS subroutine has found the optimum, INFO is set equal to 0, and the optimization is complete.

2. User Instructions

The calling statement and a description of the calling arguments is presented below:

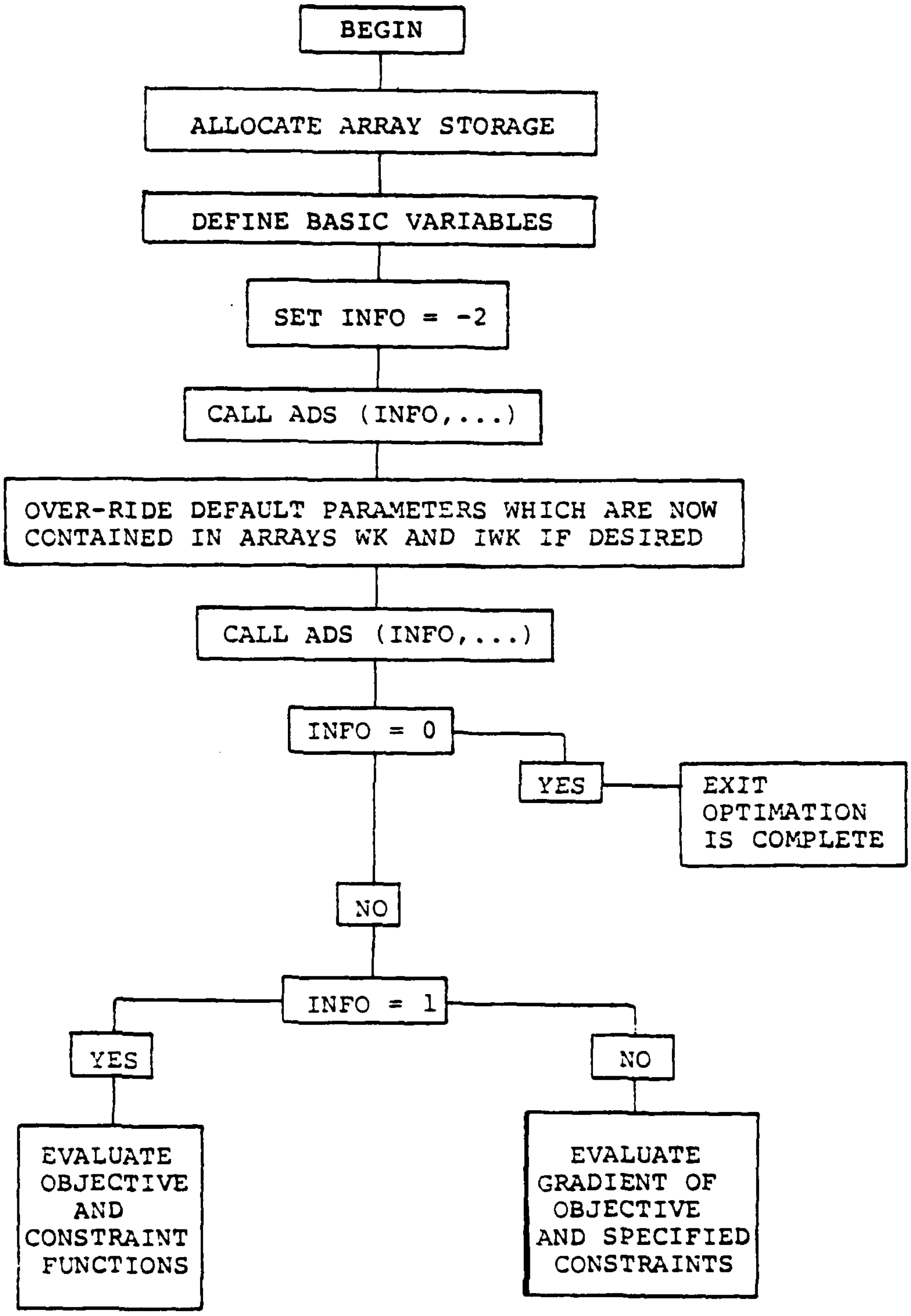


Figure 2. ADS-1 Program Logic

CALL ADS INFO, ISTRAT, IOPT, IONED, NDV, NCON, IPRINT, IGRAD, $\underline{X}$, $\underline{VLB}$, $\underline{VUB}$, OBJ, $\underline{G}$, $\underline{IDG}$, NAC, $\underline{IC}$, $\underline{DF}$, $\underline{\underline{A}}$, NRA, NCOLA, $\underline{WK}$, NRWK, $\underline{IWK}$, NRIWK

INFO

Information parameter. On the first call to ADS, INFO = -2 or 0, depending on whether the user wishes to over-ride default parameters. On subsequent calls, when control is returned to the calling program, INFO will have a value of 0, 1, or 2. If INFO = 0 on return from ADS, the optimization is complete. If INFO = 1, the user must evaluate the objective and any constraint functions and call ADS again. If INFO = 2 the user must evaluate the gradient of the objective at a specified set of constraints. If the gradient calculation control is set equal to zero, IGRAD = 0, all required gradient information will be calculated in ADS by finite difference.

ISTRAT

Optimization strategy to be used (Table 1).

IOPT

Optimizer to be used (Table 2).

IONED

One dimensional search algorithm to be used (Table 3).

NDV

Number of design variables contained in vector $\underline{X}$. NDV is the same as n in the mathematical problem statement in Equations (1) through (4).

NCON

Number of constraint values contained in vector $\underline{G}$. NCON is equal to $m+\ell$ in the mathematical problem statement given in Equations (2) and (3). NCON may be zero.

IPRINT

A four-digit print control allowing varying levels of output.

IGRAD

Gradient calculation control. If IGRAD = 0 is input to ADS, all gradient computations are done within ADS by finite difference. If IGRAD = 1, the user will supply gradient information as indicated by the value of INFO.

$\underline{X}$

Vector containing the design variables. On the first call to ADS, this is the user's initial estimate of the design, and may or may not define a feasible design. On return from ADS, it is the design for which function and gradient values are required. On the final return from ADS (INFO = 0), $\underline{X}$ contains the optimum design.

VLB

Array containing lower bounds on the design variables, $\underline{X}^{\ell}$.

VUB

Array containing upper bounds on the design variables, $\underline{X}^{u}$.

OBJ

Value of the objective function corresponding to the design defined by $\underline{X}$. OBJ has the same meaning as $F(\underline{X})$ in the mathematical problem statement given in Equation (1).

$\underline{G}$

Array containing the NCON constraint values corresponding to the current design, $\underline{X}$.

IDG

Array containing identifiers indicating the type of constraints contained in $\underline{G}$. Constraints are identified as nonlinear or linear, inequality or equality.

NAC

Number of currently active and violated constraints. NAC is defined by ADS and returned to the user.

IC

Array identifying currently active and violated constraints for which gradients are required. IC(I) gives the number of the constraint (located in array G). Array IC is defined in ADS and is returned to the user.

DF

Array containing the gradient of the objective with respect to the current values of X.

A

Array containing the gradients of the NAC constraints identified in array IC. Specifically, column J of Array A contains the gradient of constraint K, where K = IC(J).

NRA

Dimensioned rows of A.

NCOLA

Dimensioned columns of A.

WK

User provided work array for real variables. WK is used to store internal scalar variables and arrays used by ADS.

NRWK

Dimensioned size of WK.

IWK

User provided work array for integer variables. IWK is used to store internal scalar variables and arrays used by ADS.

NRIWK

Dimensioned size of IWK.

3. Strategy Options

Table 1 lists the strategies available. The parameter ISTRAT is sent to the ADS program to identify the

TABLE 1

ADS STRATEGY OPTIONS

ISTRAT	Strategy to be used
0	None. Go directly to the optimizer.
1	Sequential unconstrained minimization using the quadratic exterior penalty function method [Refs. 8,9].
2	Sequential unconstrained minimization using the linear extended interior penalty function method [Refs. 10-12].
3	Sequential unconstrained minimization using the quadratic extended interior penalty function method [Ref. 13].
4	Sequential unconstrained minimization using the cubic extended interior penalty function method [Ref. 14].
5	Augmented Lagrange Multiplier method [Refs. 15-19].
6	Sequential Linear Programming [Refs. 20, 21].
7	Method of Inscribed Hyperspheres (Method of Centers) [Ref. 22].
8	Sequential Quadratic Programming [Refs. 17, 23, 24].

strategy the user desires. The option of ISTRAT = 0 would indicate that control should transfer directly to the optimizer. This would be the case, for example, when using the Method of Feasible Directions to solve constrained optimization problems because that optimizer works directly with the constrained problem. On the other hand, if the constrained optimization problem is to be solved by creating a sequence of unconstrained minimizations, with penalty functions to deal with the constraints, one of the appropriate strategies would be used.

4. Optimizer Options

Table 2 lists the optimizers available. IOPT is the parameter used to indicate the optimizer desired. The option of IOPT = 0 is not normally used. This option is provided for program development where it is desired to access one of the one-dimensional search algorithms available in ADS.

In choosing the optimizer (as well as strategy and one-dimensional search) it is assumed that the user is knowledgeable enough to choose an algorithm consistent with the problem at hand. For example, a variable metric optimizer would not be used to solve constrained optimization problems unless a strategy is also used to create the equivalent unconstrained minimization task via some form of penalty function.

TABLE 2

ADS OPTIMIZER OPTIONS

IOPT	Optimizer to be used
0	None. Go directly to the one-dimensional search. This option is used only for program development.
1	Method of Feasible Directions (MFD) for constrained minimization [Refs. 3, 25].
2	Fletcher-Reeves conjugate direction algorithm for unconstrained minimization [Ref. 2].
3	Robust Method of Feasible Directions for constrained minimization [Ref. 4].
4	Davidon-Fletcher-Powell (DFP) variable metric method for unconstrained minimization [Refs. 26, 27].
5	Broydon-Fletcher-Goldfarb-Shanno (BFGS) variable metric method for unconstrained minimization [Refs. 28-31].
6	Newton's Method for unconstrained minimization.

5. One-Dimensional Search Options

Table 3 lists the one-dimensional search options available for unconstrained and constrained problems. Here IONED identifies the algorithm to be used. Normally the option of obtaining bounds only should not be used.

6. Allowable Combinations of Algorithms

Not all combinations of Strategy, Optimizer and One-Dimensional Search are meaningful. For example, constrained one-dimensional search is not meaningful when minimizing unconstrained functions.

Table 4 identifies the combinations of algorithms which are available in the ADS program. In the table, an X is used to denote an acceptable combination of Strategy, Optimizer and One-Dimensional Search, and it is seen that well over 100 different algorithms are possible. An example is shown by the dashed line on the table which indicates that constrained optimization is to be performed by the Augmented Lagrange Multiplier method (ISTRAT = 5) using the BFGS optimizer (IOPT = 5) and polynomial interpolation with bounds for the one-dimensional search (IONED = 4).

Because of the vast number of algorithms developed in recent years, it is clear that this list of options could be greatly expanded. One of the attributes of the ADS program is the emphasis placed on its future expansion with a minimum of effort. This flexibility is achieved through modularity of the program to avoid unnecessary duplication of common operations.

TABLE 3

ADS ONE-DIMENSIONAL SEARCH OPTIONS

IONED	One-Dimensional Search to be used [Refs. 8, 32]
1	Find brackets on the minimum of an unconstrained function.
2	Find the minimum of an unconstrained function using the Golden Section method.
3	Find the minimum of an unconstrained function using the Golden Section method followed by a cubic polynomial interpolation.
4	Find the minimum of an unconstrained function by first finding bounds and then using polynomial interpolation.
5	Find the minimum of an unconstrained function by polynomial interpolation/extrapolation without first finding bounds on the solution.
6	Find brackets on the minimum of a constrained function.
7	Find the minimum of a constrained function by using the Golden Section method.
8	Find the minimum of a constrained function using the Golden Section method followed by cubic polynomial interpolation.
9	Find the minimum of a constrained function by first finding bounds and then using polynomial interpolation.
10	Find the minimum of a constrained function by polynomial interpolation/extrapolation without first finding bounds on the solution.

TABLE 4

ADS PROGRAM OPTIONS

Optimizer Strategy	0	1	2	3	4	5	6
0	X	X	X	X	X	X	X
1	0	0	X	0	X	X	X
2	0	0	X	0	X	X	X
3	0	0	X	0	X	X	X
4	0	0	X	0	X	X	X
(5)	0	0	X	0	X	(X)	X
6	0	X	0	0	0	0	0
7	0	X	0	X	0	0	0
8	0	X	0	0	0	0	0
One-Dimensional Search							
1	X	0	0	0	0	0	0
2	X	0	X	0	X	X	X
3	X	0	X	0	X	X	X
4	X	0	X	0	X	(X)	X
5	X	0	X	0	X	X	X
6	X	0	0	0	0	0	0
7	X	X	0	X	0	0	0
8	X	X	0	X	0	0	0
9	X	X	0	X	0	0	0
10	X	X	0	X	0	0	0

7. Design Example

The 10-bar truss shown in Figure 3 was designed using the ADS program to demonstrate a few of the capabilities available. This example is a favorite design example for structural synthesis [Refs. 33-35].

The cross-sectional areas of 10 members are taken as independent design variables with stress limits and minimum gage constraints imposed on each member. The minimum gage is 0.10 square inches. The stress limits are ± 25,000 psi for all members except member 9 which has a stress limit of ± 50,000 psi. The specific weight of the material is 0.1 pounds per cubic inch and the total weight is to be minimized.

It is recognized that direct optimization in member space is not the best approach for structural optimization problems such as this, where approximation techniques are applicable. Indeed, even without using approximation techniques, a better problem formulation would be to treat reciprocals of the member areas as the design variables. However, the purpose here is simply to demonstrate the optimization capability of ADS, noting that design efficiency can be greatly improved through careful problem formulation.

The results for various combinations of Strategy, Optimizer and One-Dimensional Search are listed in Table 5, but for brevity, all possible combinations are not included.

The optimum weights achieved are an indication of reliability, whereas the number of function evaluations and

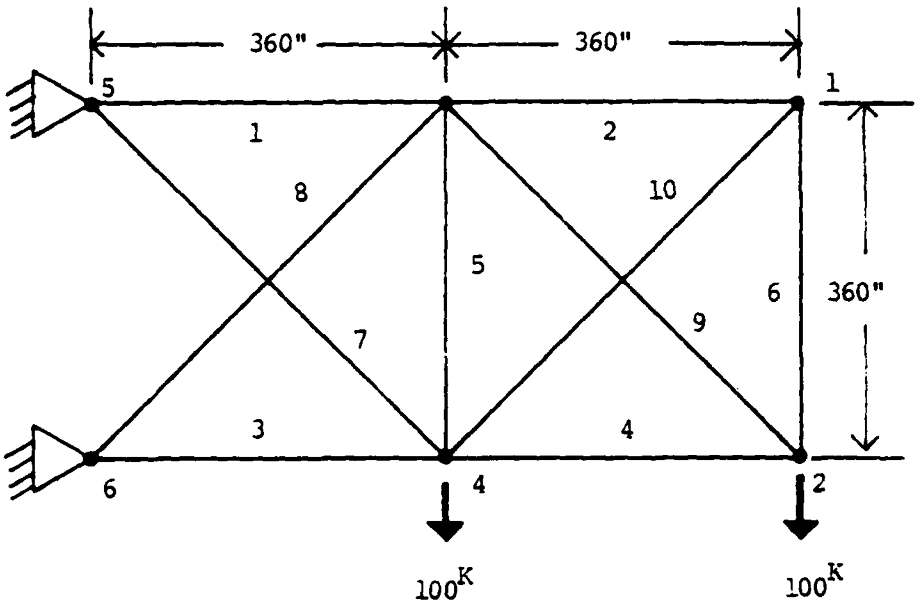


Figure 3. 10-Bar Truss

TABLE 5

DESIGN EXAMPLE OPTIMIZATION RESULTS

ISTRAT	IOPT	IONED	Optimum Weight	Number of Analyses	Number of Gradients
0	1	7	1516.8	305	39
0	1	8	1532.3	321	37
0	1	9	1519.7	120	30
0	1	10	1530.1	119	31
0	3	8	1497.8	489	8
0	3	9	1497.3	114	6
1	2	4	1648.8	114	27
1	4	2	1534.2	384	37
1	4	5	1549.4	109	33
1	5	4	1575.2	159	35
2	2	4	1603.4	216	46
2	4	5	1522.7	133	41
2	5	2	1505.2	528	51
2	5	3	1635.7	456	40
3	2	3	1619.4	428	39
3	4	4	1511.3	211	51
3	5	2	1505.2	528	51
3	5	5	1713.8	93	29
4	2	3	1617.2	489	45
4	5	2	1505.2	528	51
4	5	4	1500.8	209	52
4	4	5	1718.8	70	22
5	2	3	1527.3	518	48
5	4	4	1504.0	210	47
5	5	4	1496.3	235	54

gradient computations provides a measure of relative efficiency. From Reference 35, the minimum known weight for this problem is 1497.61 pounds.

Caution should be exercised in drawing conclusions from one example because, in general, both efficiency and reliability of a given algorithm is problem dependent. Also, the results given here are preliminary based on a March, 1983 version. Program development is continuing and significant refinements have already been made.

F. OPTIMIZATION SUMMARY

The foregoing material is intended to be only an introduction to optimization. The body of material written on optimization is vast and the curious reader can consult any of the numerous references for further information. The descriptions included above are deliberately brief but should equip the reader to become a user of optimization. While research continues to seek improvements in optimizers, it is sufficient for most preliminary designs to "get close quickly." As an initial design becomes more refined, it may be possible to improve upon that design by using a more sensitive optimizer. Thus, a quick rough estimate could then be refined by a more precise algorithm. Whenever the design goal of an engineer can be mathematically expressed, that goal can be optimized. Sound engineering judgement is still required and with practice, an engineer can more skillfully pose the problem for optimization.

As a general purpose, state-of-the-art, user-friendly optimization program, ADS is an excellent program to use. The examples presented in this work will demonstrate the usefulness of optimization techniques for the design of marine reduction gears.

III. DEVELOPMENT OF MARGO

A. *INTRODUCTION*

Naval combatants are conceived in response to national defense policies. Because policy is subject to change and interpretation, so are the designs of warships. While such changes generate considerable consternation for the designer, they are a way of life in the democratic process of military procurements. Accordingly, several sets of military characteristics may be under consideration until the Congress approves the final form and funds are appropriated for a new ship class.

These military or combat characteristics of a warship are first defined as performance criteria such as maximum speed, endurance, and reliability. The choice of prime movers may be nuclear, gas turbine, steam, diesel, or any combination thereof. The make-up of the combat systems suit is defined and redefined in response to competitive programs and interests. Thus, the translation of combat characteristics into concrete design terms is not an easy process. In fact, the process is an on-going one and subject to a great deal of criticism and frustration when late changes result in additional cost and delay. Unfortunately for the military designer, there is very little control over the political forces which generate design changes. Rather than chafe at

these inevitable changes, the Navy's design team, Naval Sea Systems Command must cope with the situation, and the only reasonable response is to be flexible.

Flexibility is best achieved by the careful development of reliable computer algorithms which duplicate the logical thoughts of an experienced designer. A reliable computer algorithm could be used to quickly respond to "what if" questions and would reduce the natural frustration that develops from the posing of such questions.

With such thoughts in mind, MARGO is presented as a modest illustration of the potential of computer programs which combine the mathematics of optimization with the logic of machinery design.

B. THE GEAR DESIGN PROCESS

Because machinery design is an iterative process, it is difficult to describe the beginning. The usual procedure is to assume one value and derive several others until something detrimental is discovered. However, this first value must originate from an informed idea of what the completed gear set will be. In order to have an idea of what the completed gear set will be like, specifications are written which describe its completed form. The drafting of specifications is subject to the same uncertainties described above, but sooner or later the specifications will be decided. In the following examples, it is assumed that a double reduction helical gear set is to be designed for a 50,000 shaft

horsepower (SHP) guided missile destroyer such as the DDG-51 class presently being designed. The ship is to be powered by four General Electric LM-2500 marine gas turbines (MGT's) with a full power prime mover speed of 3600 RPM. Full power RPM for the main shaft is to be 160 RPM for an overall reduction ratio of 22.50. With these specifications, the marine engineer must consider the following items in the design synthesis.

1. Materials

The kind of steel to be used is among the first and most important decisions to be made. Material selection is normally the perogative of the manufacturer in the sense that a design bid is submitted with a particular steel in mind. Considerable attention must be given to material selection because of its impact on cost, ease of production, and reliability. For the purposes of initial design, it must be determined what yield strength and hardness are required. An upper limit is arbitrarily set in order to contain the design iterations within the range that actual gears can be manufactured. Material constraints have long been and will continue to be the area most subject to change in the design of machinery. As harder and stronger materials become available, machinery designs will be developed which exploit the latest materials.

At present the hardness of bull gears largely determines the design possibilities of marine reduction gears.

In general, the harder and stronger the steel, the smaller and lighter the gear box will be for a given SHP rating. Weight is a critical item of interest in warship construction and minimum weight is foremost on the list of priorities for a warship power plant. Less weight means less cost, especially in the form of life cycle cost for fuel. In addition, the military characteristics of the ship mean that as much weight as possible must be conserved in order to fit the desired combat systems configuration on the ship and to reserve space and weight for future growth. The CG-47 class cruiser is an excellent example. At 9,700 tons of displacement, this ship was designed to be the combat equivalent of the Russian Kirov class cruiser which displaces 22,000 tons. Clearly, U.S. warships are lighter in weight and smaller in size than their Soviet counterparts.

2. Gear Size

The size of gears is the area in which the number of possible combinations is infinite. Ideally, a gear should be sized to just handle its maximum design load and not breakdown until the end of its design life. Because of the interest in minimum weight, modern marine gears are of welded construction. Welded construction permits a wide range of sizes and upper limits for gears are determined by the physical dimensions of heat treatment furnaces. However, the overall dimension of a gear box is limited to what will fit through America's transportation network. Unless the

manufacturing plant is located close to a seaport and transportation is to be by barge, railroad tunnel clearances dictate the maximum height of a gear box. Indeed, the military's primary cargo plane, the C-5A was designed to conform to this limit and 13 feet 2 inches is the upper limit on horizontal size for any military materiel requiring transportation by air or rail.

The objective in gear sizing is to build a gear large enough and strong enough to handle its full power specification and yet not be excessively overbuilt. The size is determined by the transmitted torque, speed, and allowable stresses. The allowable stresses in turn depend on the material used, its heat treatment, surface life and design life. To develop an improved design, multiple iterations of the design are required.

The allowable surface compressive stresses and the applied load will determine the minimum gear pitch diameter and face width. The allowable bending stress will determine the minimum tooth size, measured by diametral pitch or module [Ref. 36]. Allowable stresses are given in AGMA Standards [Refs. 37 and 38].

In high speed continuous duty gear applications, such as marine reduction gears and turbine drives, a very high number of load cycles may be accumulated on the gear teeth. A warship operating at standard speed (15 knots) with a 60% operations tempo for 30 years would accumulate nearly 10^{10}

cycles. For these high cycle applications, it is recommended that the AGMA allowable stresses be reduced by the factors listed in Table 6.

TABLE 6

ALLOWABLE STRESS FACTORS

No. Cycles	Allowable Stress Factors
10^7	1.00
10^8	0.90
10^9	0.81
10^{10}	0.729
10^{11}	0.656
10^{12}	0.590

The next step is to determine the required gear sizes in terms of pitch diameter, center distance, and face width. The Hertz equation for surface compressive stress is arranged as follows for helical marine reduction gears:

$$d \gtrsim \left[\frac{0.7\ TE\ (mg+1)\ \cos^2\phi\ k_d}{s_{ca}^2\ \ F\ mg\ \sin\psi\ \cos\phi\ mp}\right]^{1/3} \qquad (7)$$

$$C = \frac{d}{2}\ (mg+1) \qquad (8)$$

where:

C = Center distance;

d = Pitch diameter, pinion;

E = Modulus of elasticity of gear material;

F = Facewidth of gear or pinion;

mg = Gear ratio = D/d;

mp = Profile contact ratio;

k_d = Total derating factor (Assume = 2 for initial designs)

$$K_d = K_0 K_m K_v$$

K_0 = Overtorque factor;

K_m = Mounting factor;

K_v = Dynamic Load Factor;

T = Torque input to pinion;

ψ = Helix angle;

ϕ = Normal pressure angle

Many of the gear design variables discussed above may be unfamiliar. The best source of information on the definition and geometry of gear variables is AGMA Standard 115.01 titled "Basic Gear Geometry." Appendix A contains descriptive figures of some of the common gear design variables and their symbols.

3. Tooth Size

After determining the minimum pinion and gear diameters, the tooth size must be selected. For high speed marine reduction gears, the general preference is to use as fine a pitch

as possible within the limits imposed by tooth bending stress. This preference is based on the belief that minimized sliding velocities will reduce scoring and noise.

However, it is wise to size the teeth such that the critical stress used to determine gear life will be surface compression and not tooth bending. Using this criteria, cumulative fatigue is more apt to result in pitting than breakage. Pitting damage is more likely to be detected in its early stages from excessive noise or vibration or from periodic visual inspections of the gears (Naval gears are visually inspected once a quarter). Should a marine reduction gear fail first by breakage, the consequences are likely to include a complete failure of the gear train which is an unacceptable risk. For this reason, tooth bending stress is conservatively determined.

The sizing of gear tooth proportions is a whole science unto itself. Reference 39 discusses various popular tooth forms and Appendix A contains a descriptive figure of gear tooth design variables. However, the following equations are a good starting point but require considerable iteration.

$$N_p = 15\left[\frac{mg + 2.5}{mg}\right] \cos \phi \qquad (9)$$

where:

N_p = number of pinion teeth.

$$P \geq \frac{N_p}{P \cos \Phi} \qquad (10)$$

where:

P = Diametral pitch.

$$d_f = \frac{N_p}{P \cos \Phi} \qquad (11)$$

where:

d = Final pinion pitch diameter.

Determining the addendum also requires multiple iterations of the equation:

$$a = 1 + 0.5(m_p \pi \cos \phi_t)^2 \left(\frac{1}{N_p} - \frac{1}{N_g}\right) \qquad (12)$$

where:

m_p = Profile contact ratio;
1.65 for ϕ = 20
1.55 for Φ = 22.5
1.45 for ϕ = 25

ϕ_t = Transverse pressure angle;

N_p = Number of teeth in pinion;

N_g = Number of teeth in gear.

A crucial factor in gear design is shaft size. In practice, the shaft size drives the gear size. This facet

further compounds the iteration process and profoundly impacts the geometric arrangement of the gear box. Manual means of iteration are difficult because the designer has difficulty grasping the sensitivity of one variable's impact upon another. For this reason, iteration by computer, especially by optimization techniques, is the fastest and most reliable means available to find an optimum design. The optimizer calculates the necessary gradient information to steer the iterations toward an improved design. Human iteration is often frustrated by the inability to determine a "search direction" which results in an improved design.

C. PROGRAM ORGANIZATION

1. Brief Overview

MARGO consists of a main program which utilizes numerous supporting subroutines. A data file formatted in accordance with the instructions contained in Appendix B supplies the master program with required information from the user. Once the user has formatted the data file, the program is executed by entering the command word "MARGO." Depending upon the variables contained in the data file, MARGO will perform weight minimization or noise minimization. A third option is design analysis which does not require any calls to the optimization program ADS. A flow chart of the program is illustrated in Figure 4.

2. Master Program

The master program manages the various logical sequences as directed by the user via the data files. Initial

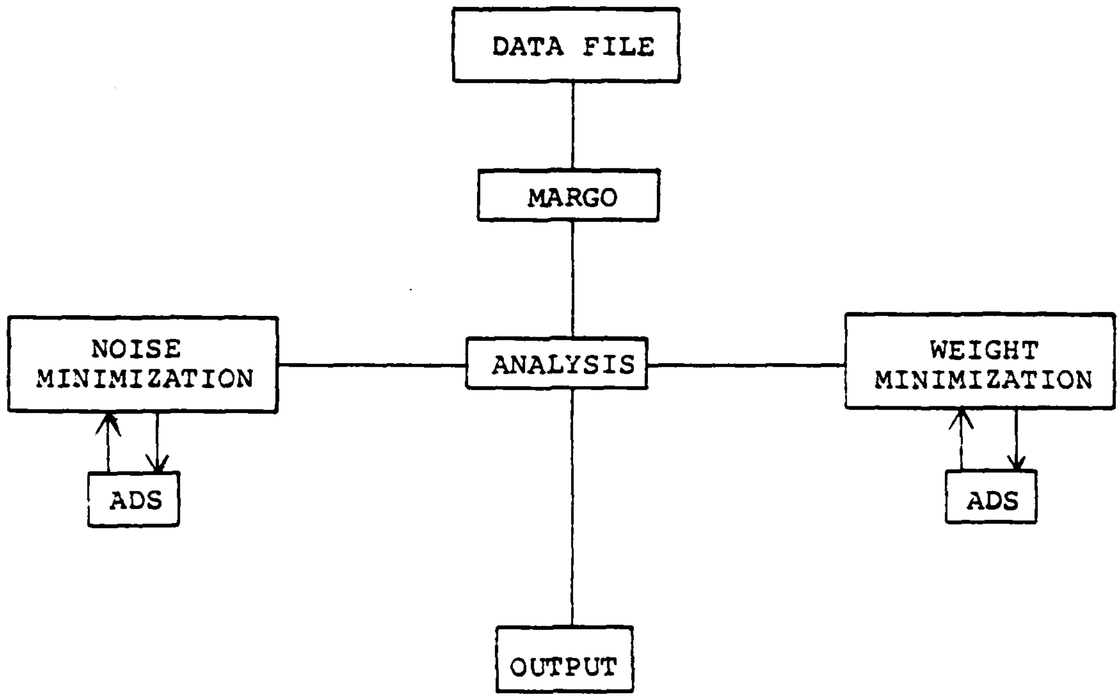


Figure 4. MARGO Flow Chart

design data is read from the data file and design parameters are stored. The program option selected is then executed by utilizing the necessary sequence of supporting subroutines. The program has no provision for interactive use although such a feature could be easily added. An interactive option was omitted because of the excessive time required to manipulate the program on a modem connected terminal.

The program is designed for use by carefully selecting data for the data file prior to execution. Once the data file is submitted, as in a batch processing system,

no further action is required by the user except to pick up the output for subsequent review. If the user has access to a "hard wired" terminal (i.e., connected directly to the main frame computer), the program can be executed and reviewed on the terminal. Execution time depends on the computer system and how many users are logged on the system. The examples discussed in this work were run on the IBM-3033 with 50-100 users logged on and execution times ranged from less than 10 seconds to 3 or 4 minutes. Longer execution times depend on the optimization strategy selected and the initial design's starting point relative to the minimum.

While the program can be run sitting at a terminal, it is difficult to comprehend the output unless the user is interested in only one variable, for example total weight. Otherwise, the 5-10 pages of output should be carefully reviewed to ensure that the data is reasonable. There are some internal checks for unreasonable values which will be highlighted in the output but the user is cautioned to carefully input the data.

3. Supporting Subroutines

The supporting subroutines for MARGO are listed in Table 7. Subroutines are numbered MRGXXX and the number sequence generally represents the sequence for use. Each subroutine is self-documented and normally narrow and specific in purpose. There are no global variables and each subroutine is self-contained. Calling arguments are clearly delineated

TABLE 7

MARGO SUPPORTING SUBROUTINES

Number	Purpose
MRG001	Gear tooth number combinations
MRG002	Transverse Pressure Angle (ϕ_t)
MRG003	Pitches and Tooth Proportions
MRG004	Line of Action (Z)
MRG005	Ratios and Factors
MRG006	Loads
MRG007	Tooth Data
MRG008	Radius Calculations
MRG009	Involute Geometry Factors
MRG010	Geometry Factors
MRG011	Beam Stress and Stress Concentration Factors
MRG012	Compressive Stresses and Tip Scoring Factors
MRG013	Help Module (Reserved for development of interactive features)
MRG014	Aggregate Contact Ratio (for noise minimization)
MRG015	Weight Estimates

with respect to input and output values. The variables used within each subroutine are defined therein. Variable names conform with the standard definitions established by the AGMA [Ref. 40].

The subroutine system employed lends itself to modular development and further improvement especially in the area

of improved "objective function" programs. For instance, reliable equations for noise minimization are apt to be either classified or proprietary in nature. By following the examples presented for weight and noise minimization, combined with the information presented in Chapter II on the use of ADS, users should be able to pose more complicated and reliable equations for optimization.

D. USER OPTIONS

MARGO has three user options which are selected in accordance with the instructions contained in Appendix B.

1. Design Analysis

Option I is similar to the other two options except that the optimization program is not called. The values for weight and aggregate contact ratio (ACR) are calculated but the basic design variables are not adjusted. This option is useful for checking the design analysis of the manufacturer or of a previously manufactured gear for comparison purposes. Design analysis calculations take less than 10 seconds on the IBM-3033 and are expected to take less than a minute on the VAX Model 11/780 computer.

The weight estimation subroutine (MRGO15) is "calibrated" to reflect the weight of a gear set completely constructed of welded gears such as the gear set manufactured for the FFG-7 class. Thus, the weight estimates of older designs such as the DDG-2 class will be considerably lighter than their

actual weights because welded construction was uncommon on earlier marine reduction gears.

2. Weight Minimization

Option II performs weight minimization using the weight estimation subroutine mentioned above. The "initial design" is submitted via the data file and all possible design parameters are eligible for optimization within prescribed limits. The details and procedures for use of this option are presented in the MARGO User's Manual contained in Appendix B.

The purpose of the weight estimation subroutine is to provide a relative measure of design improvement. While the estimated weight is probably within 5% of the manufactured weight for a welded gear set, the weight estimate should be used with caution for any other application.

3. Noise Minimization

Option III uses the equation for aggregate contact ratio and is a very rudimentary prediction of radiated noise. Extensive research is underway to accurately predict noise estimates and much of this research is classified when applied to military applications. In order to avoid working with classified material, this work deliberately avoided more serious consideration of noise minimization. However, the interest in noise minimization is probably more important for the design of submarine reduction gears and the subject is

addressed in order to attract the attention of submarine reduction gear designers to optimization techniques.

The details and procedures for use of this option are also contained in the MARGO User's Manual, Appendix B.

IV. TOOTH COMBINATIONS

A. INTRODUCTION

To determine the tooth combinations for the design of a marine reduction gear, the gear designer needs two specifications:

1) reduction ratio
2) reduction ratio tolerance

The first task for the designer is to find a combination of tooth numbers that yield the specified reduction ratio within the allowable tolerance. The equation for the overall gear ratio of a double reduction gear set is:

$$R = \frac{N2}{N1} \times \frac{N4}{N3} \qquad (13)$$

where:

N1 = Number of teeth on the first reduction pinion;

N2 = Number of teeth on the first reduction gear;

N3 = Number of teeth on the second reduction pinion;

N4 = Number of teeth on the second reduction gear.

In the past, manual methods of selecting gear tooth numbers were complicated because large reduction gears for marine propulsion required that each tooth on a pinion

contact each tooth on a gear before the same teeth mesh again. Known as a "hunting tooth" design, this requirement was stipulated in order to prevent uneven wear patterns from developing on the teeth while the gear teeth were cold worked during initial operation. The litmus test for determining if a tooth combination is a "hunting tooth" design is to check for common factors. A mathematical definition for no common factors is "conjugate" and the terms "hunting tooth design" and "conjugate set" are used hereafter to mean the same thing.

For instance, the combination of 10 and 20 is not a "hunting tooth" combination because the digits 2, 5 and 10 are common factors of the number 20. However, the combination 13 and 20 is a "hunting tooth" combination because 13 is a prime number and not a factor of 20. It is for this reason that many gear sets are manufactured using prime numbers for either the pinion or the gear. However, there are many other possible combinations that will satisfy the "hunting tooth" criteria, like 9 and 20. Neither number is a prime number, but the digits 3 and 9 are not common factors of 20.

The difficulty arose when the designer had to satisfy all three criteria at once; reduction ratio, reduction ratio tolerance, and the hunting tooth criteria. Since the choice of tooth numbers is constrained, considerable time was required to find a conjugate set by manual methods. However, these stringent requirements are no longer required for modern

marine propulsion gears because advanced materials negate the necessity for a hunting tooth design altogether.

In the past, bull gears were manufactured with Brinell hardness numbers around 200. For materials this soft, cold working would occur when the gears were first placed in operation. In order to insure that this cold working was evenly distributed, the hunting tooth design criteria was applied except that prime numbers greater than 113 were undesirable due to manufacturing limitations.

Material science and today's industrial capability now allow bull gears to be hardened to Brinell 300-350. Cold working does not occur with gears of this hardness and the hunting tooth combination is no longer required to prevent cold working. However, there may be other reasons for the continued use of the hunting tooth combination and the subroutine presented in this work makes the use of hunting tooth combinations very easy to attain.

For instance, considerable research is being conducted in the area of reduction gear noise quieting. Besides the industrial interest in noise reduction for machinery there are many military applications of noise quieting for reduction gears especially in the field of anti-submarine warfare. The number of gear teeth meshing in a reduction gear plays a significant role in the amount of noise generated by a reduction gear. In order to provide a convenient computational means of selecting and changing tooth combinations, a special subroutine

was written. The subroutine MRG001 finds a conjugate set quickly and enables the designer to consider different combinations. A nonconjugate set can be found even faster for those designs where a hunting tooth combination is neither required or desired. MRG001 also allows a manufacturer to use a gear previously designed for another application by finding three other tooth numbers that satisfy all three criteria.

B. THE EFFECT OF TOLERANCE ON THE POPULATION OF CONJUGATE SETS

The effect of tolerance on the population of conjugate sets for any given reduction ratio significantly impacts the time required for the computer to search and locate a satisfactory set. Yet, the reduction ratio tolerance has a less significant effect upon the performance of the gear set. For instance, the proposed reduction ratio and tolerance for the Navy's newest destroyer design (DDG-51) is 22.50 ± 0.01. The tolerance could actually be larger. Given a prime mover speed of 3600 RPM and the DDG-51's reduction ratio of 22.50, the propeller shaft is turning 160 RPM at full power. A specified tolerance of 22.50 ± 0.01 means less than a 0.1 RPM change at full power.

$$\frac{3600}{22.51} = 159.9289 \qquad \frac{3600}{22.49} = 160.0711$$

The full power performance of a propeller is, for all practical purposes, not affected by a ±1 or 2 RPM difference. Using this criteria, the reduction ratio tolerance could be increased to ± 0.14.

$$\frac{3600}{159} = 22.6415 \qquad \frac{3600}{161} = 22.3602$$

Table 8 illustrates the effect of tolerance selection on the number of conjugate sets or "hunting tooth designs" for a specified reduction ratio of 22.50. As the numbers in Table 8 illustrate, the population of conjugate sets declines with smaller tolerance. Selecting an arbitrarily small tolerance increases the search time for the computer to find a set of tooth numbers. Variable pitch propellers make the reduction ratio selection even less restrictive and unless a designer has a special reason for specifying a small tolerance, the largest possible tolerance should be allowed.

Notice in Table 8 that the results for T = 0.00001 and T = 0.000001 are identical. These results are identical because a finite number of ratios are equal exactly to 22.50, for example:

$N1 = 35$

$N2 = 78$

$N3 = 52$

$N4 = 525$

$$R = \frac{N2}{N1} \times \frac{N4}{N3} = \frac{78}{35} \times \frac{525}{52} = 22.5 \text{ EXACTLY}$$

TABLE 8

EFFECT OF TOLERANCE ON POPULATION OF CONJUGATE SETS

FOR R = 22.50

TOLERANCE	SETS CONSIDERED	SETS TESTED	CONJUGATE SETS
0.1	2,684,834,520	8,221,289	4,477,834
0.01	"	823,444	306,656
0.001	"	102,604	30,980
0.0001	"	43,896	3,199
0.00001	"	42,290	1,817
0.000001	"	42,290	1,817

NOTES:

"Sets Considered" = The total number of different ratios (NUM/DENOM) formed.

"Sets Tested" = The total number of different ratios within the specified tolerance.

"Conjugate Sets" = The total number of different ratios which passed the tolerance test AND the conjugate test.

Minimum Number of Teeth = NL = 35

Maximum Number of Teeth = NM = 850

N1 Ranges From Nl - 25% NM

N2 Ranges From 2·NL - NM

N3 Ranges From NL - 25% NM

N4 Ranges From 7·NL - NM

The population of conjugate sets is more than 8.2 million for a tolerance of T = 0.1. This figure is more than 13 times as large as the population for T = 0.01. It follows that the computer could find a conjugate set for T = 0.1 over 13 times faster than for a set where the tolerance is specified for T = 0.01. The examples listed in Table 9 further illustrate the speed of computation versus tolerance for a specified reduction ratio of R = 22.50:

TABLE 9

SPEED OF COMPUTATION VERSUS TOLERANCE

TOLERANCE	N1	N2	N3	N4	RA	CPU Time Seconds
0.1	35	71*	35	387	22.4302	0.17
0.01	35	79*	35	349*	22.5069	0.33
0.001	35	88	39	349*	22.4996	30.83
0.0001	35	78	52	525	22.5000	126.63

where:

RA = Actual Reduction Ratio

* Indicates Prime Number

No Tooth Number Was Specified

The examples presented above were obtained on an IBM-3033 computer. The IBM-3033 is a very large, fast computer

and may not be available to the designer. However, the VAX Model 11/780 found the same example set for T = 0.01 in less than 5 CPU seconds.

To show that the results for DDG-51's reduction ratio (R = 22.50) are not unique, Table 10 presents the population sizes for several other United States Navy warship reduction ratios for T = 0.01.

C. PROGRAM METHOD DEVELOPMENT

Reference 41 describes the manual methods of finding hunting tooth combinations by conjugate fraction methods and proposes a computer algorithm for the process. However, the example presented in Reference 41 includes two sets which have a common factor of 2 and the actual FORTRAN program which was used is not revealed. Nevertheless, the general method proposed in Reference 41 was used as a starting point for the development of subroutine MRG001.

MRG001 sequentially forms two sets of integer pairs. The first pair represents the product of the tooth numbers for the two pinions and the second pair represents the product of the two gears. The equations used are:

$$\mathrm{NUM} = \mathrm{N2} \times \mathrm{N4} \tag{13}$$

$$\mathrm{DENOM} = \mathrm{N1} \times \mathrm{N3} \tag{14}$$

Yielding:

TABLE 10

POPULATION OF CONJUGATE SETS FOR UNITED STATES NAVY WARSHIPS

CLASS	R	SETS CONSIDERED	SETS TESTED	CONJUGATE SETS
CGN-36	18.72	2,684,834,520	1,159,764	427,137
DD-963	21.4864	"	842,836	312,459
DDG-51	22.50	"	823,444	306,656
FFG-7	20.00	"	1,037,245	381,719

NOTES:

R = Reduction Ratio

"Sets Considered" = The total number of different ratios (NUM/DENOM) formed.

"Sets Tested" = The total number of different ratios within the specified tolerance.

"Conjugate Sets" = The total number of different ratios which passed the tolerance test AND the conjugate test.

Tolerance = T = 0.01 for each case.

Minimum Number of Teeth = NL = 35

Maximum Number of Teeth = NM = 850

$$R = \frac{N2 \times N4}{N1 \times N3} = \frac{NUM}{DENOM} \qquad (15)$$

NUM and DENOM are formed by four nested "do loops" so that N1, N2, and N3 are held fixed while N4 loops through all of its permissible values. Then N2 is incremented to its next value and N4 is looped through its permissible values again. Once N2 has looped through all of its permissible values, N3 is incremented and the process repeats itself until N1 is incremented through the full range of its allowed values.

A simple example will illustrate the method. Let N1, N2, N3 and N4 each range from 1 to 3; then the iteration values are as follows:

Iteration Number	N1	N3	N2	N4	
1	1	1	1	1	
2	1	1	1	2	
3	1	1	1	3	
4	1	1	2	2	*
5	1	1	2	3	
6	1	1	3	3	**
7	1	2	1	1	
8	1	2	1	2	
9	1	2	1	3	
10	1	2	2	2	**
11	1	2	2	3	
12	1	2	3	3	**
13	1	3	1	1	
14	1	3	1	2	
15	1	3	1	3	
16	1	3	2	2	**
17	1	3	2	3	

Iteration Number	N1	N3	N2	N4	
18	1	3	3	3	**
19	2	2	1	1	**
20	2	2	1	2	
⋮	⋮	⋮	⋮	⋮	
35	3	3	3	3	

At the position marked with an asterisk "*," the loop restarts at N4 = 2 because the product for 1 × 2 is the same as 2 × 1 (the commutative law of multiplication). By stepping the increment of N4, valuable computation time is saved and the algorithm avoids duplicate combinations with tooth numbers juxtaposed. For the example above, this feature provides a 56% improvement in efficiency because there are only 35 different ratios (NUM/DENOM) while there are 3^4 = 81 different combinations for these numbers. For the same reasons, the positions marked with a double asterisk "**" have a stepped increment.

In actual practice, the magnitude of this efficiency is even more pronounced. The data in Table 8 considered over 2.6 billion different ratios, while the number of different combinations is equal to $(850-35)^4$ or over 441 billion combinations. Without this 99% increase in efficiency, an IBM-3033 computer would take over 36 days of CPU time to process 441 billion ratios. Any procedure which constrains the area of the search will increase speed. Additional search speed efficiency is achieved by exploiting the observations described below.

Table 11 illustrates the tooth combinations and reduction ratios of several warships in the United States Navy. A close look at these gear sets reveals that first reduction gears (N2) have from 2 to 4 times as many teeth as first reduction pinions (N1) have. Likewise, bull gear teeth (N4) are apt to be at least 7 times the number of second reduction pinion teeth. Table 12 contains the tabulated ratios of gear tooth numbers to pinion tooth numbers. This point is easily visualized by remembering that the overall reduction gear ratio is the product of the first and second reductions. In the case of the DDG-51's reduction ratio of 22.50, it is clear that numbers around 3 and 7 will form a product equal to 22.50. The user can exploit any knowledge of what the general range of first and second reduction ratios ought to be for the gear set being designed. Since the first reduction pinion is unlikely to have more than 4 times the minimum number of teeth, the N1 loop should be constrained between the minimum number of teeth (NL) and 4*NL. In a similar manner, the designer may decide that the first reduction gear will have no more than 25% of the maximum number of teeth allowed (NM).

The minimum number of pinion teeth is constrained in order to prevent undercutting and recommended minimums are published by the American Gear Manufacturers Association (AGMA). For instance, the AGMA recommends tooth proportions for fine-pitch involute spur and helical gears and specifies

TABLE 11

UNITED STATES NAVY WARSHIP REDUCTION GEARS

CLASS	SHP	N1	N2	N3	N4	R	MANUFACTURER	YEAR
DD-963	40,000	99	235	58	525	21.4864	Westinghouse	1974
FFG-7	40,000	46	119	53*	410	20.0123	Western Gear	1976
CGN-36	**	HP 41*	94	43*	351	18.7154	General Electric	1971
		LP 43*	99					
CVN-68	**	HP 51	152	59*	517	26.1163	General Electric	1971
		LP 63	142					
SSN-681	**	74	285	99	776	30.1884	DeLaval	1972

* Indicates Prime Number

** SHP Classified or Unavailable

TABLE 12

REDUCTION GEAR-TO-PINION RATIOS

CLASS	N2/N1	N4/N3
CGN-36	HP 94/41 = 2.3 LP 99/43 = 2.3	351/43 = 8.2
CVN-68	HP 152/51 = 3.0 LP 142/63 = 2.6	517/59 = 8.8
DD-963	235/99 = 2.4	525/58 = 9.1
FFG-7	119/46 = 2.6	410/53 = 7.7
SSN-681	285/74 = 3.9	776/99 = 7.8

the minimum number of pinion teeth as a function of helix angle and normal pressure angle. The recommended minimum number of fine-pitch teeth ranges from 6 to 32 teeth, while the minimum number of coarse-pitch pinion teeth for marine propulsion gear sets is usually higher.

The designer should adjust the internal values of MRG001 according to the gear design under consideration. For the data presented in this paper, the following values were used:

Minimum Number of teeth = NL = 35

Maximum Number of teeth = NM = 850

N1 ranges from	NL	to	16% NM		(35 to 140)
N3 ranges from	N1	to	16% NM		(N1 to 140)
N2 ranges from	2×NL	to	50% NM		(70 to 426)
N4 ranges from	7×NL	to	100% NM		(245 to 850)

Once MRG001 has formed two product pairs, the ratio of the pairs is compared to determine which ratios fall within the specified tolerance. As mentioned above, the tolerance specification plays a major role in determining the population size of conjugate sets. Sets within the specified tolerance are then tested for conjugacy by using the FORTRAN math function "MOD," which returns the remainder of one number divided by another. For example, X = MOD (10,2) will set X = 0 because the remainder of 10/2 is 0, and Y = MOD

(11,2) will set Y = 1 because the remainder of 11/2 is 1. MRG001 loops through each integer from 2 to the number of pinion teeth. The loop begins at 2 because MOD (10/1) = 0. The zero value indicates that 1 is a factor of 10. If 10 is the number of teeth in a pinion and 17 is the number of teeth in the corresponding gear, MRG001 would have decided that 1 is a factor of 10 and also of 17 and reject the pair. However, 1 is a common factor of every number, but for the purposes of meeting the hunting tooth criteria, 1 is an acceptable common factor. To prevent MRG001 from rejecting all such combinations, the conjugate test loops begin at 2.

When a hunting tooth design is required, MRG001 performs a conjugate test on each pair of teeth and both sets must pass the test to be returned as a conjugate set. As soon as a common factor is found between a pinion and gear set, the pair is rejected and the sequential search for another set is resumed. Sets which pass the conjugacy test are returned to the master program.

In order to avoid consideration of any gear or pinion with a prime number greater than 113, a conditional test is performed after each loop is incremented. Prime numbers greater than 113 and less than 997 are incremented by an additional 1. As mentioned above, manufacturing limitations vis-a-vis the numbers of teeth on a hobb preclude the manufacture of a gear or pinion with these numbers.

V. COMPARATIVE DESIGN RESULTS

A. INTRODUCTION

The comparison of optimized designs with older reduction gears must be considered carefully. Modern techniques for manufacturing reduction gears place great emphasis upon conserved weight. Thus, a comparison of the DDG-2 class guided missile destroyer's reduction gear (built in 1960) with an optimized modern design would have little meaning. Hence, the comparisons included in this work begin with the DD-963 class, which is considered a turning point design. Designs prior to DD-963 paid less attention to weight and designs after DD-963 were considered weight critical. The FFG-7 class frigate reduction gear followed as a design that was clearly intended to be light-weight. Finally, a sample design for the DDG-51 class guided missile destroyer is presented. Although DDG-51's reduction gear is still being designed, the sample design included herein will serve as an interesting future comparison to the designer's estimate of weight and to the gear's actual manufactured weight.

B. THE DD-963 CLASS DESTROYER

Table 13 contains a summary of design variables for the DD-963 class destoryer. Listed alongside the actual design variables are the optimized counterparts corresponding to

TABLE 13

DD-963 REDUCTION GEAR DESIGN VARIABLES

Variable		Actual Value	Optimized Value
General Data			
SHP		40,000	Same
Reduction Ratio		21.4864	21.4843
Weight		167,500	159,823
First Reduction			
Normal Diametral Pitch		6.0	4.2309
Transverse Diametral Pitch		5.437847	3.8345
Helix Angle		25°	25°
Pressure Angle		14.5°	14.5°
Pitch Line Velocity		279.1 ft/sec	405.6 ft/sec
Facewidth (+ 1.87 gap = 19.12)		17.25	29.875
Center Distance		30.7107	43.552
Reduction Ratio		2.3737	2.3737
Number of Teeth:	Pinion	99	99
	Gear	235	235
Pitch Diameter:	Pinion	18.2057	25.8185
	Gear	43.2156	61.2863
Second Reduction			
Normal Diametral Pitch		4.0	6.1265
Transverse Diametral Pitch		3.625231	5.5525
Helix Angle		25°	25°

TABLE 13 (CONT.)

Variable		Actual Value	Optimized Value
Pressure Angle		14.5°	14.5°
Pitch Line Velocity		103.3 ft/sec	166.9 ft/sec
Face Width (2.52 gap = 35.02)		32.30	25.33
Center Distance		80.4087	53.399
Reduction Ratio		9.0517	9.0508
Number of Teeth:	Pinion	58	59
	Gear	525	534
Pitch Diameter:	Pinion	15.9990	10.6259
	Gear	144.8184	96.1730

each variable. The actual weight for the DD-963's reduction gear is 167,500 pounds and the optimized weight is 159,823, a savings of 7677 pounds.

To arrive at this optimum, the MARGO data file was first calibrated to reflect the material properties of the material used in the DD-963 reduction gear. Since the details of such information is proprietary in nature and not in the public domain, the values for design bending stress and design shear stress were manipulated until the MARGO weight estimate was fairly close to the actual weight. In this case, the MARGO weight estimate was 167,541 pounds or just 41 pounds over the actual weight. The optimization program was then executed using material properties that are quite similar to the actual materials.

The savings in weight is accomplished by selecting design variables which allow each component to be stressed to its upper limit. This situation should not be disturbing. After all, an upper limit is by definition the maximum allowed value for a variable. Upper limits and appropriate K factors should be adjusted if an additional margin of safety and reliability is desired.

C. THE FFG-7 CLASS FRIGATE

The actual and optimized design variables for the FFG-7 class frigate are presented in Table 14. The actual weight of the FFG-7 reduction gear is 114,168 pounds and the MARGO estimate is 114,370, or 202 pounds over the actual weight.

TABLE 14

FFG-7 REDUCTION GEAR DESIGN VARIABLES

Variable		Actual Value	Optimized Value
General Data			
SHP		40,000	Same
Reduction Ratio		20.0123	20.0027
Weight		114,168	98,262
First Reduction			
Normal Diametral Pitch		4.43	6.8159
Transverse Diametral Pitch		3.8309	5.8941
Helix Angle		30.145°	30.15°
Pressure Angle:	Pinion	6°	16.0°
	Gear	16°	16.0°
Pitch Line Velocity		163.1 ft/sec	122.6 ft/sec
Facewidth (+ 2.75 gap = 21.75)		19.0	16.4519
Center Distance		18.623	13.997
Reduction Ratio		2.58696	2.5870
Number of Teeth:	Pinion	46	46
	Gear	119	119
Pitch Diameter:	Pinion	12.0077	7.8044
	Gear	31.0634	20.1896
Second Reduction			
Normal Diametral Pitch		3.5	6.1074
Transverse Diametral Pitch		3.0948	5.4005
Helix Angle		27.840°	27.84°

TABLE 14 (CONT.)

Variable		Actual Value	Optimized Value
Pressure Angle		14.5°	14.5°
Pitch Line Velocity		237.9 ft/sec	162.9 ft/sec
Facewidth (+ 3.25 gap = 31.25)		28.00	19.7825
Center Distance		66.143	45.274
Reduction Ratio		7.73585	7.7321
Number of Teeth:	Pinion	53	56
	Gear	410	433
Pitch Diameter:	Pinion	17.125	10.3695
	Gear	132.4765	80.1784

The MARGO weight estimate was obtained by using the same method described above for the DD-963. The optimized weight is 98,262 or a 13.9 percent improvement of the actual weight.

While the optimized weights for both the DD-963 and FFG-7 reduction gears are only slightly less than the actual designs, each of the optimized designs were attained in less than 5 CPU seconds on an IBM-3033 computer. Setting up the data files for the MARGO program took less than ten minutes each. It is likely that the actual designs were obtained after weeks of effort by several engineers. Thus, MARGO can be used to quickly locate a design starting point for further analysis by hand or for more detailed analysis by another computer code.

D. THE DDG-51 CLASS GUIDED MISSILE DESTROYER

Since the DDG-51 class guided missile destroyer is in the process of being designed, a comparison of actual design variables with optimized variables is not possible. Nevertheless, Table 15 lists the optimized design variables for subsequent comparison.

E. NOISE MINIMIZATION RESULTS

Noise minimization results were found to be the antithesis of weight minimization results. In general, lightweight gears are noisier than heavier-weight gears. This is logical because less energy is required to vibrate small masses than large masses. The most likely use of noise

TABLE 15

DDG-51 REDUCTION GEAR OPTIMIZED DESIGN VARIABLES

Variable		Optimized Value
General Data		
SHP		50,000
Reduction Ratio		22.50299
Weight		115,993
First Reduction		
Normal Diametral Pitch		3.7399
Transverse Diametral Pitch		3.2341
Helix Angle		30.15°
Pressure Angle		15.7904°
Pitch Line Velocity		170.0 ft/sec
Facewidth		20.7567
Center Distance		16.388
Reduction Ratio		2.0286
Number of Teeth:	Pinion	35
	Gear	71
Pitch Diameter:	Pinion	10.8223
	Gear	21.9538
Second Reduction		
Normal Diametral Pitch		6.710
Transverse Diametral Pitch		5.9333
Helix Angle		27.84°

TABLE 15 (CONT.)

Variable		Optimized Value
Pressure Angle		14.1589°
Pitch Line Velocity		113.8 ft/sec
Facewidth		17.9899
Center Distance		43.820
Reduction Ratio		11.0930
Number of Teeth:	Pinion	43
	Gear	477
Pitch Diameter:	Pinion	7.2472
	Gear	80.3931

minimization in conjunction with weight minimization is to treat weight as a constraint. For instance, find the quietest gear design that weighs no more than 120,000 pounds. The optimization results will probably be a gear designed as close as possible to the maximum allowed weight. An alternate method would be to impose a maximum noise index and let the design weight be as small as possible for the noise limitation. However, work in this area depends upon a more reliable means of analysis and noise measure.

VI. CONCLUSIONS

A. THE VALUE OF OPTIMIZATION TECHNIQUES

The results in Chapter V illustrate the considerable time to be saved by using an optimization code. Once the fundamental program is written for the analysis of a gear system, the optimizer allows considerable flexibility in experimenting with design boundaries. Probing the limits of design possibilities via optimization is faster than manual methods. Human manipulation of a multitude of design variables is very difficult. An improving avenue of design possibilities may be abandoned as the result of a math error. Computer programs are the most reliable means for performing repetitive computations. By necessity, the design process requires multiple iterations. While a human may tire of such repetition, a computer is unaffected. Thus, the two factors of error and repetition make optimization techniques a desirable approach.

B. MARGO APPLICATIONS

While MARGO was designed for large marine reduction gears in the 40,000 SHP range, it is also applicable to smaller gear sets. By selecting the appropriate factors, MARGO could be used to analyze and design double reduction gear sets for generators and for lighter duty marine propulsion drives. Basically any double reduction helical

gear could be designed and with very minor modifications, spur gears as well.

C. AREAS FOR FURTHER DEVELOPMENT

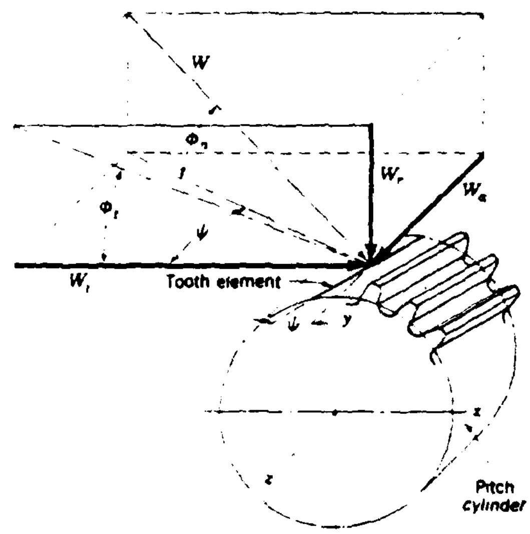
The area most important in military reduction gear design is noise reduction. Much of the mathematics associated with noise involves complex numbers. With an increase in the mathematical difficulty of noise equations, the chances for human error dramatically increase. As soon as a credible analysis is found to represent the noise characteristics of a reduction gear, that analysis should be structured as a subroutine compatible with MARGO. By following the example procedures for the DDG-51 weight minimization problem, a sophisticated noise minimization subroutine can be formulated. MARGO can then be modified with the appropriate conditional branches and read statements to call ADS for the optimization. It should also be noted that the examples presented above were formulated as unconstrained minimization problems. Constraints on noise limitations are a logical area for future expansion.

A secondary area of improvement is to expand the data calculated by MARGO. Tooth geometry factors could be calculated in greater detail. Subroutines to design shafting, bearings, and lubrication requirements are also needed. A library routine of past designs would be useful for comparing the trends of various design variables.

ADS can be used for any optimization problem. Its flexibility is demonstrated by MARGO, but its capabilities are far greater than the modest example presented. It is hoped that MARGO has served as an introduction to its capability and will inspire further applications.

APPENDIX A

FIGURES SHOWING GEAR DESIGN VARIABLES



W = Total Force

W_a = Axial Component or Thrust Load

W_r = Radial Component

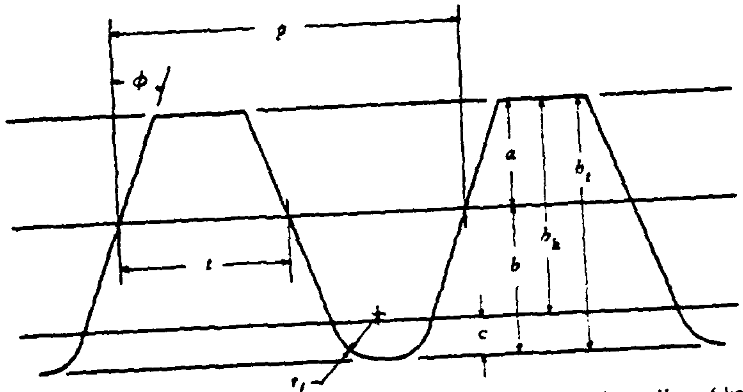
W_t = Transmitted Load

ϕ_n = Normal Pressure Angle

ϕ_t = Transverse Pressure Angle

ψ = Helix Angle

Figure 5. Basic Gear Elements



a = addendum
b = dedendum
c = clearance

b_k = working depth
b_t = whole depth
p = circular pitch

r_f = fillet radius of basic rack
t = circular tooth thickness – basic
ϕ = pressure angle

Figure 6. Involute Gear Teeth

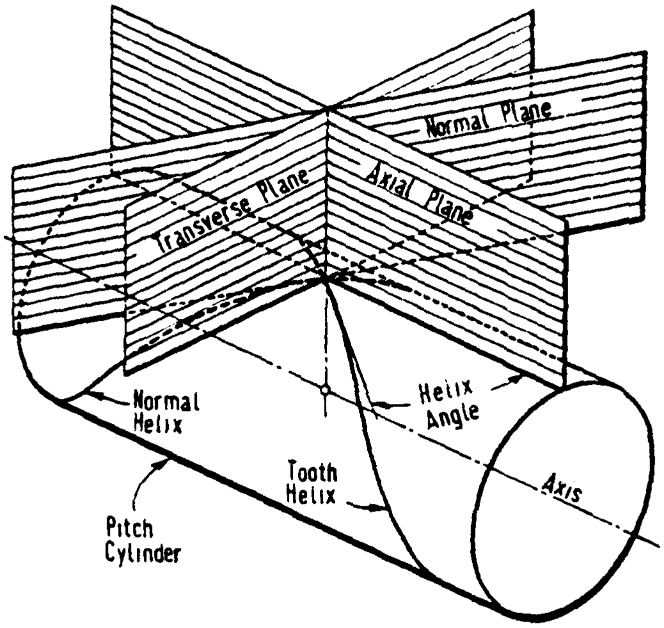


Figure 7. Transverse, Axial and Normal Gear Planes

APPENDIX B

MARGO USER'S MANUAL

1. INTRODUCTION

Version 1 of MARGO is written for use by means of a data file. The user edits a data file named "MARGO DATA" to enter the desired initial design values. The program is executed with the command word "MARGO." The MARGO exec is written and installed at the Naval Sea Systems Command Design Automation Center to perform the utility commands associated with compiling and running the program. After the MARGO command word is entered, the program is executed without any further input from the user. Printed output can be picked up at the user's designated pick-up point for subsequent review.

While Chapter II discusses the use of ADS, MARGO Version 1 does not allow the user to externally adjust or select any of the optimization parameters described therein. The optimization options used within MARGO are described in Section 5 of this appendix. Users who desire to experiment with different optimization strategies should make a copy of the MARGO program under another name and modify the optimization segment to suit the user's needs. MARGO and its supporting subroutines are self-documented and modification should be easy with a printed copy of the program to edit.

MARGO reserves space for an interactive option. However, this option was not developed in Version 1 in view of the limited access to terminals directly connected ("hard-wired") to the main computer at the Naval Sea Systems Command Design Automation Center. Interactive operation on a remote terminal with less than a 1200 baud data transfer rate is undesirable. Initial versions of the program were run in an interactive mode on an IBM-3033 computer and compared to the VAX Model 11/780. The IBM runs considerably faster than the VAX, but even on the VAX the analysis program can be run in less than 1 CPU minute.

2. HOW TO USE MARGO

An initial data set is provided for the DDG-51. This data set should be copied and stored under a new name such as "DDG51 DATA." The "MARGO DATA" file can be edited and changed to the user's preference. Once the data set is fixed, save the file and execute the program by entering the command word "MARGO." The data is echo-printed in the output under both print output options (Detailed and Summary print options). Thus, the key to using Version 1 is editing the data file to reflect the desired values. The data file values are explained below.

3. DATA FILE

The data file consists of 30 data lines described below and summarized in Table 16. A sample data file is presented

in Figure 8. Additional data lines may be added by the user and inserted in Segment 0000, INITIAL DATA INPUT of the master program. Integer data are in format I10 and real data are in format F15.5. This system makes a sight-check of the data file easy.

Data Line Number 1: ITCON

ITCON = Iteration Control. This variable determines the iteration option of the user according to the following single integer code placed in column 10.

0 = Interactive mode (reserved for subsequent) modifications)

1 = Analysis only

2 = Optimization and Analysis (of the optimum)

Data Line Number 2: IOC

IOC = Integer Optimization Code. This variable determines the optimization path desired according to the following single integer code placed in column 10.

0 = No Optimization (use this code for analysis only)

1 = Noise minimization

2 = Weight minimization

Data Line Number 3: IPC

IPC = Integer Print Control. IPC determines the level of printed output desired according to the following single integer code placed in column 10.

1 = Summary Output Only

2 = Detailed Output

Data Line Number 4-7: N1, N2, N3, N4

N1 = number of teeth on the first reduction pinion.

N2 = number of teeth on the first reduction gear.

N3 = number of teeth on the second reduction pinion.

N4 = number of teeth on the second reduction (bull) gear.

When ITCON = 1, analysis is performed on the designated design for the number of teeth specified and the conjugate tooth finder subroutine is not called. When ITCON = 2, the conjugate tooth finder subroutine MRG001 is called. Any single tooth number can be specified or a complete tooth set can be specified and MRG001 will find the next sequential set. See Chapter IV for additional information about the use of subroutine MRG001. Tooth numbers must be right justified beginning in column 10. Placing zeros in column 10 will cause MRG001 to find a proper tooth combination for design.

Data Line Number 8-9: AAD(1), AAD(2)

AAD(1) = the helix angle for the first reduction and AAD(2) = the helix angle for the second reduction. When ITCON = 1, analysis is performed according to the specified helix angle. When ITCON = 2, helix angle is treated as a design variable by ADS and will be adjusted to its optimum value. Values are written in degrees with the decimal point in column 10.

Data Line Number 10-11: APND(1), APND(2)

APND(1) = the normal pressure angle for the first reduction mesh and APND(2) = the normal pressure angle for the second reduction mesh. When ITCON = 1, analysis is performed according to the specified pressure angles. When ITCON = 2, normal pressure angle is treated as design variable by ADS and will be adjusted to its optimum value. Values are written in degrees with the decimal point in column 10.

Data Line Number 12-13: BL(1), BL(2)

BL(1) = the backlash for the first reduction mesh and BL(2) = the backlash for the second reduction mesh. Normal values range from 0.010-0.020 inches. Values are written with the decimal point in column 10.

Data Line Number 14: BUL

BUL = Bearing Unit Load and is used in the weight estimation subroutine MRG015. A normal value is 300 psi. Write the value as a real number with the decimal in column 10.

Data Line Number 15-16: F(1), F(2)

F(1) = the facewidth of the first reduction mesh and F(2) = the facewidth of the second reduction mesh. When ITCON = 1, analysis is performed using the indicated values. When ITCON = 2, ADS will adjust facewidth as a design variable and determine its optimum value. Values are written as real numbers with the decimal point in column 10.

Data Line Number 17: FLT

FLT = the locked train factor. Since MARGO is written for double reduction gear sets, set FLT = 2.0 with the decimal point in column 10.

Data Line Number 18: HP

HP = the horsepower to be transmitted to the main shaft (SHP). Write this value as a real number with the decimal point in column 10.

Data Line Number 19-20: P(1), P(2)

P(1) = the diametral pitch of the first reduction mesh and P(2) = the diametral pitch for the second reduction

mesh. When ITCON = 1, analysis is performed using the indicated value. When ITCON = 2, ADS treats diametral pitch as a design variable and will adjust its value to the optimum. Write diametral pitch as a real number with the decimal in column 10.

Data Line Number 21: PT
PT = propeller thrust and is used in the weight estimation subroutine MRG015. A value of 500,000 pounds is typical for design purposes. Write this value as a real number with the decimal in column 10.

Data Line Number 22: R
R = the specified reduction ratio when designing and the actual reduction ratio when analyzing.

Data Line Number 23-24: RF(1), RF(2)
RF(1) = tooth fillet radius for the first reduction mesh and RF(2) = tooth fillet radius for the second reduction mesh. A normal value for design purposes is 0.02 inches. Write these values as real numbers with the decimal in column 10.

Data Line Number 25: RPM
RPM = the revolutions per minute for the prime mover driving the reduction gear. For the LM2500 marine gas turbine, this value is 3600 rpm. Write this value as a real number with the decimal point in column 10.

Data Line Number 26-27: RT(1), RT(2)
RT(1) = the edge radius of the generating rack for the first reduction mesh and RT(2) = the edge radius of the generating rack for the second reduction mesh. Write these values as real numbers with the decimal in column 10.

Data Line Number 28: SDB
SDB = design bending stress. Use 12,500 psi as a normal design point. Write this value as a real number with the decimal point in column 10.

Data Line Number 29: SDS
SDS = design shear stress. Use 7,500 psi as a normal design point. Write this value as a real number with the decimal in column 10.

Data Line Number 30: T
T = the reduction ratio tolerance specified for an initial design. See Chapter IV for additional information about specifying T. This value is only used when the tooth combination subroutine MRG001 is called. Write this value as a real number with the decimal point in column 10.

TABLE 16

MARGO DATA FILE LINE DESCRIPTIONS

Data Line Number	MARGO Variable	Remarks
1	ITCON	Iteration Control
2	IOC	Integer Optimization Code
3	IPC	Integer Print Control
4	N1	First Reduction Pinion Teeth
5	N2	First Reduction Gear Teeth
6	N3	Second Reduction Pinion Teeth
7	N4	Second Reduction Gear Teeth
8	AAD(1)	First Reduction Helix Angle
9	AAD(2)	Second Reduction Helix Angle
10	APND(1)	First Reduction Pressure Angle
11	APND(2)	Second Reduction Pressure Angle
12	BL(1)	First Reduction Backlash
13	BL(2)	Second Reduction Backlash
14	BUL	Bearing Unit Load
15	F(1)	First Reduction Facewidth
16	F(2)	Second Reduction Facewidth
17	FLT	Locked Train Factor
18	HP	Horsepower
19	P(1)	First Reduction Pitch
20	P(2)	Second Reduction Pitch
21	PT	Propeller Thrust
22	R	Reduction Ratio
23	RF(1)	First Reduction Tooth Fillet Radius
24	RF(2)	Second Reduction Tooth Fillet Radius
25	RPM	Prime Mover RPM
26	RT(1)	First Reduction Edge Radius of Generating Rack
27	RT(2)	Second Reduction Edge Radius of Generating Rack
28	SDB	Design Bending Stress
29	SDS	Design Shear Stress
30	T	Reduction Ratio Tolerance

Column Numbers 1 2 12345678901234567890123	Data Line Number	Data Item
1	1	ITCON
2	2	IOC
1	3	IPC
0	4	N1
0	5	N2
0	6	N3
0	7	N4
25.0	8	AAD(1)
25.0	9	AAD(2)
20.0	10	APND(1)
20.0	11	APND(2)
0.02	12	BL(1)
0.02	13	BL(2)
300.0	14	BUL
18.0	15	F(1)
20.0	16	F(2)
2.0	17	FLT
50000.0	18	HP
3.0	19	P(1)
3.5	20	P(2)
500000.0	21	PT
22.50	22	R
0.02	23	RF(1)
0.02	24	RF(2)
3600.0	25	RPM
0.300	26	RF(1)
0.300	27	RF(2)
12500.0	28	SDB
7500.0	29	SDS
0.01	30	T

Figure 8. Sample MARGO Data File

Note: Integer data is in format I10 and real data are in format F15.5. This system makes a sight-check of the data file easy (i.e., the decimal points line up with single digits).

4. MARGO ORGANIZATION

MARGO is self-documented to the extent that each variable is defined within each subroutine and all variables are defined within the master program. In addition, the master program is divided into segments which are clearly identified.

The segment numbers and their contents are defined as follows:

Segment 0000	Initial Data Input
Segment 1000	Data File Echo-Print
Setment 2000	Interactive Option (reserved space)
Segment 7000	Optimization
Segment 7100	Noise Minimization
Segment 7200	Weight Minimization
Segment 7300	Noise and Weight Minimization (reserved space)
Segment 8000	Help (reserved space)
Segment 9000	Printer Output Options

5. MARGO ADS PARAMETERS

MARGO's ADS parameters for weight minimization are imbedded in the main program in segments 7000 and 7200.

These parameters must be changed within the main program. Later versions of MARGO can be modified to permit external changes to be selected values at the option of the user. However, this option was omitted in Version 1 in order to reduce the burden on beginning users. The design variables used in the program for weight minimization are summarized in Table 17 and their ADS translations are listed in Table 18.

TABLE 17

DESIGN VARIABLES FOR WEIGHT MINIMIZATION

Design Element	MARGO Variable	Lower Bound	Upper Bound
Facewidth	F(1)	10.0	24.0
	F(2)	18.0	36.0
Pressure Angle	APND(1), APND(2)	5.0	25.0
Helix Angle	AAD(1), AAD(2)	10.0	35.0
Pitch	P(1), P(2)	2.0	8.0

MARGO's ADS parameters for noise minimization are imbedded in Segments 7000 and 7100 of the main program. Because the noise minimization objective function is not considered to be a reliable measure of noise, only the first reduction mesh is analyzed. This procedure is considered an acceptable indication of relative noise measure since the first reduction mesh operates at higher speeds than the

AD-A136 352 DESIGN OPTIMIZATION OF MARINE REDUCTION GEARS(U) NAVAL POSTGRADUATE SCHOOL MONTEREY CA W T BRAMLETT SEP 83 2/2

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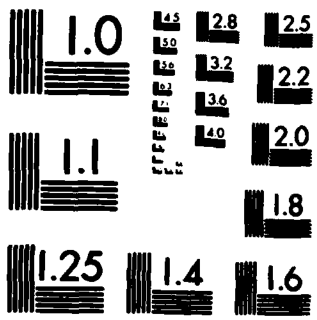

MICROCOPY RESOLUTION TEST CHART
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TABLE 18

ADS PARAMETERS FOR WEIGHT MINIMIZATION

ADS Parameter	MARGO Value
NRA	10
NCOLA	5
NRWK	1000
NRIWK	800
INFO	0
ISTRAT	0
IOPT	5
IONED	4
IPRINT	2220
IGRAD	0
NDV	8
NCON	0
X(1)	F(1)
X(2)	F(2)
X(3)	APND(1)
X(4)	APND(2)
X(5)	AAD(1)
X(6)	AAD(2)
X(7)	P(1)
X(8)	P(2)
VLB(1)	10.0
VLB(2)	18.0
VLB(3)	5.0
VLB(4)	5.0
VLB(5)	10.0
VLB(6)	10.0
VLB(7)	2.0
VLB(8)	2.0
VUB(1)	24.0
VUB(2)	36.0

TABLE 18 (CONT.)

ADS Parameter	MARGO Value
VUB(3)	25.0
VUB(4)	25.0
VUB(5)	35.0
VUB(6)	35.0
VUB(7)	8.0
VUB(8)	8.0
OBJ	TW (Total Weight)

second mesh. For this reason, the first reduction mesh generates more ambient noise than the second reduction mesh.

This argument ignores the effects of harmonics which carry farther in water for lower frequency sounds such as those generated by the second reduction mesh. However, a detailed discussion of the noise characteristics of reduction gears with respect to underwater sound detection is not possible in this work because of the classified nature of such subjects. Thus, the noise measure minimized is ambient noise.

The noise minimization design variables are summarized in Table 19, and Table 20 lists the ADS parameters used.

TABLE 19

DESIGN VARIABLES FOR NOISE MINIMIZATION

Design Element	MARGO Variable	Lower Bound	Upper Bound
Effective Facewidth	FE(1)	10.0	24.0
Transverse Pressure Angle	APTD(1)	18.0	30.0
Helix Angle	AAD(1)	10.0	40.0
Pinion Base Diameter	DBP(1)	8.0	40.0
Active Tooth Depth	ATD(1)	5.0	40.0

TABLE 20

ADS PARAMETERS FOR NOISE MINIMIZATION

ADS Parameter	MARGO Value
NRA	10
NCOLA	5
NRWK	1000
NRIWK	800
INFO	0
ISTRAT	0
IOPT	1
IONED	9
IPRINT	2220
IGRAD	0
NDV	5
NCON	0
X(1)	FE(1)
X(2)	APTD(1)
X(3)	AAD(1)
X(4)	DBP(1)
X(5)	ATD(1)
VLB(1)	10.0
VLB(2)	18.0
VLB(3)	10.0
VLB(4)	8.0
VLB(5)	5.0
VUB(1)	24.0
VUB(2)	30.0
VUB(3)	40.0
VUB(4)	40.0
VUB(5)	40.0
OBJ	ACR(1) (Aggregate Contact Ratio)

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